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Size-Resolved Characteristics, Governing Processes, and Health Implications of Atmospheric Metals: A Review

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ABSTRACT

Atmospheric particulate matter acts as a carrier of toxic metals, posing significant risks to environmental quality and human health, yet their size-dependent behavior remains insufficiently synthesized. This study aims to review the distribution and controlling mechanisms of metals and mercury across particle sizes. A systematic synthesis of studies published over the past two decades was conducted, focusing on global research patterns, sampling approaches, analytical techniques, size distribution characteristics, influencing factors, and associated health impacts. Results indicate that research is concentrated mainly in East Asia and Europe, with limited data from tropical and developing regions. Size-segregated sampling is commonly performed using cascade impactors and micro-orifice uniform deposit impactors, while chemical analyses rely on techniques such as inductively coupled plasma mass spectrometry, X-ray fluorescence, atomic absorption spectrometry, cold vapor atomic fluorescence spectrometry, and direct mercury analyzers. Three dominant distribution patterns are identified, including fine-mode enrichment of toxic metals, bimodal distributions influenced by mixed sources, and coarse-mode dominance of crustal elements. Fine particles are primarily associated with combustion and secondary formation, whereas coarse particles originate from natural sources. Mercury exhibits distinct behavior due to its transformation and partitioning processes, with particulate-bound mercury often concentrated in accumulation-mode particles. Health-related findings highlight that smaller particles enhance the potential for deep lung deposition of toxic metals. Overall, this review provides an integrated understanding of size-resolved metal behavior and highlights critical research gaps, supporting future monitoring strategies and risk management.

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1. Introduction

Atmospheric particulate matter (PM) is a complex mixture of solid particles and liquid droplets with diverse sizes, chemical compositions, and sources. It plays an important role in the atmospheric processes and has significant impacts on environmental quality and human health [1]-[3]. One of the most important properties of PM is particle size, usually described by aerodynamic diameter (Dp). Particle size affects how PM is formed, how far it can travel, where it is deposited, and how deeply it can enter the human respiratory system [2]-[7]. PM is often divided into several groups, including nucleation mode (Dp < 0.01 µm), Aitken mode (0.01 - 0.1 µm), accumulation mode (0.1 - 1 µm), intermediate mode (1 - 2.5 µm), and coarse mode (Dp > 2.5 µm) [8]-[12]. These particle groups have different physical behavior, chemical composition, and emission sources [13]-[16]. Very small particles usually dominate number concentration, while larger particles in accumulation and coarse modes contribute more to mass concentration [13], [14]. Nucleation particles are often related to combustion and secondary formation, while coarse particles mainly come from dust and sea salt [17]-[20]. The

accumulation mode is especially important because it can carry many secondary compounds and metals due to its large surface area and active gas-particle reactions [15], [16]. Therefore, particle size is a useful indicator for understanding PM sources and atmospheric processes. Among PM components, metals are a major concern because of their toxicity, persistence, and ability to accumulate in the environment. Metals such as arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), and nickel (Ni) are known to be harmful, and some are classified as human carcinogens [21], [22]. Their toxic effects are mainly related to the production of reactive oxygen species (ROS), which can cause oxidative stress, DNA damage, and cell problems [21], [23], [24]. In addition, Pb and Cd can build up in organs such as the liver, kidneys, and nervous system, leading to long-term diseases [21], [25], [26]. Mercury (Hg) is considered especially dangerous because it can directly affect the central nervous system, even at low concentrations. Studies have linked Hg exposure with neurological disorders, reduced cognitive ability, cardiovascular disease, and kidney damage [27]-[31]. Methylmercury is even more dangerous because it can cross the blood-brain barrier and placenta, thereby creating higher risks for infants and children [28], [31]-[33].

Most metals naturally exist in soil, water, air, and living organisms, but increasing atmospheric concentrations caused by human activities have become a serious problem [34]-[37]. Natural sources include rock weathering, desert dust, and volcanic emissions, while human sources include fossil fuel burning, transport, metallurgy, and biomass burning [19], [38]-[40]. In the atmosphere, most metals are attached to particles, and their behavior strongly depends on particle size. In contrast, atmospheric Hg exists in several forms, among which gaseous elemental mercury (GEM) is the dominant species. Due to its low water solubility and a long atmospheric lifetime of about 0.5 - 1 year, GEM can travel long distances and become globally distributed [21], [27], [41], [42]. Global Hg emissions remain high, and East and Southeast Asia contribute around 40% of total emissions [32], [33]. The harmful effects of atmospheric metals depend not only on concentration but also on particle size. Many studies show that anthropogenic metals such as Pb, Zn, Cd, and As are often concentrated in fine particles ($PM_{2.5}$), while crustal metals such as Al, Fe, and Ca are mainly found in coarse particles [43]-[45]. Fine particles can stay longer in the air and travel farther, increasing regional transport. They can also enter deep into the lungs and even reach the bloodstream, raising health risks [12], [45], [46]. Mercury shows a different pattern because it mainly exists in the gas phase. Particle-bound mercury (PBM) forms after gaseous elemental mercury is oxidized to gaseous oxidized mercury (GOM), followed by gas-particle partitioning [28], [32], [33], [47], [48]. PBM is often concentrated in the accumulation mode (about 0.3-1.0 μm), which reflects the importance of condensation and heterogeneous reactions in its formation [49]-[52].

Overall, particle size and metal composition strongly control the environmental behavior, transport ability, and toxicity of atmospheric aerosols. However, current knowledge is still incomplete, especially across different metals, particle sizes, and regions. Therefore, this review summarizes studies from the last two decades on the size distribution of metals and Hg, with focus on sources, controlling processes, and health risks. This review may help identify research gaps, improve monitoring strategies, and support better pollution control and health protection in the future.

2. Global Distribution Of Size-Resolved Studies On Atmospheric Metals And Hg.

A total of 35 studies were selected for synthesis over two decades based on three criteria: (i) studies of atmospheric metals and/or Hg, (ii) use of size- resolved sampling methods, and (iii) provision of clearly identifiable study sites. As shown in Figure 1, a pronounced spatial clustering of studies in East Asia and Europe, with particularly high sampling densities in coastal and urban environments. Recurrently investigated locations include Beijing, Shanghai, Nanjing, and multi-city regions in China, as well as Thessaloniki, London, Poland, and northern Italy in Europe [12], [49], [52]-[60]. In contrast, observational coverage remains sparse across many parts of the world, particularly throughout much of Southeast Asia, South America, Africa, and large areas of South Asia, despite several studies reported from Thailand [61], [62]. Figure 1 also shows that studies focused specifically on Hg are substantially fewer than those addressing other metals, revealing a clear imbalance in current research attention. This is noteworthy given the distinct atmospheric behaviour of Hg, including multiphase transformations,

gas-particle partitioning, and efficient long-range transport. In East Asia, several coastal locations include both HM and Hg investigations, implying that interactions between marine aerosols and anthropogenic emissions may be particularly relevant in these environments. Altogether, the current literature remains geographically unbalanced, highlighting the need for additional long-term observations in underrepresented regions (e.g., Southeast Asia, South America, and Africa) to achieve a more comprehensive understanding of atmospheric metals and Hg.

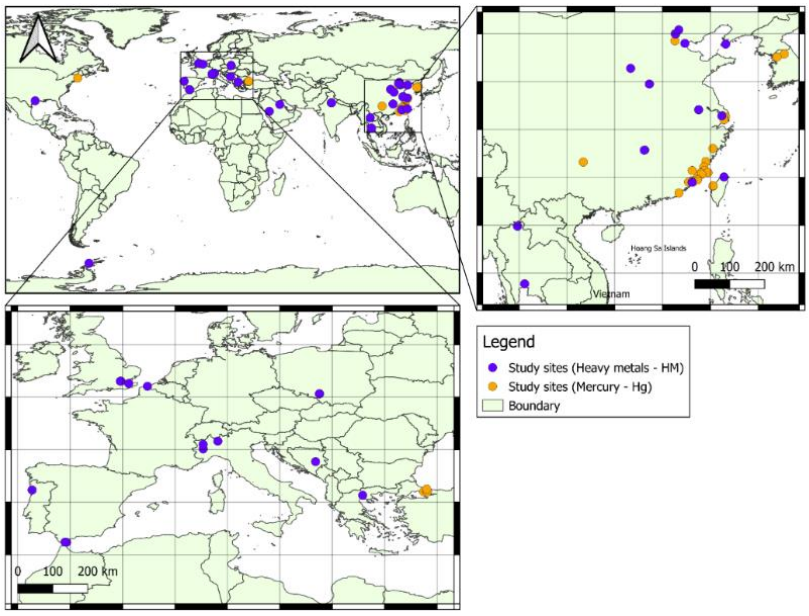

Figure 1. *Global spatial distribution of Metals and Hg studies in PM, based on the studies summarized in Table 2. Purple dots represent Metals studies, while orange dots represent Hg studies.*

3. Sampling And Analysis Methods In Size-Resolved Studies.

The method of sampling and chemical analysis of size-resolved PM plays a crucial role in ensuring accuracy, reliability, and comparability between studies. Size-sorted sampling systems operate on the principle that PM of different sizes and masses will have different trajectories in the airflow, thus allowing them to be separated into distinct segments according to aerodynamic diameter [63].

Investigations of atmospheric metals and Hg in PM typically employ either high-volume samplers or size-resolved sampling techniques. Among these, cascade impactors are the most widely used systems for size-segregated studies because they can separate particles into multiple aerodynamic size fractions with high resolution (Table 1), typically ranging from 5 to more than 13 stages [4], [12], [60], [64], [65]. In traditional studies, Andersen impactors are commonly used, while Low Pressure Impactor (DLPI) and Micro Orifice Uniform Deposit Impactors (MOUDI) due to their improved resolution for $PM_{<0.1}$ fractionations. Besides mechanical impactors, advanced devices such as Electrical Low-Pressure Impactors (ELPI, ELPI+) have also been applied to provide real-time information on particle size distribution, particularly useful in aerosol kinetic studies [61], [66]. In addition, some specialized systems such as rotating drum impactors or personal cascade impactor samplers (PCIS) are also used in specialized studies to assess variability over time or individual exposure [59], [67]. In parallel with size stratification systems, high-volume and medium-volume samplers are often used to collect total PM samples or in combination with impactors to ensure sufficient sample volume for detailed chemical analyses, especially for trace metals and Hg [49], [68], [69]. This combination is particularly important in Hg studies, due to low concentrations and uneven distribution between gaseous and particulate phases.

Furthermore, sample quality is greatly affected by airflow rate, sampling time, filter type, and environmental conditions [63], [70]. In particular, airflow should be maintained at the prescribed operating rate to ensure proper size-resolved performance, as samplers such as the Ambient Nano-

Sampler and Personal Nano-Sampler were operated at fixed flow rates of 40 L min^{-1} [45], [50], [51], [56], [57], [65], [71]. Higher surrounding air velocity may reduce collection efficiency shortening PM residence time within the sampling field [72]. Deviations from the nominal flow rate may also lead to insufficient PM mass or biased size classification [70]. Therefore, flow calibration and quality control (QA/QC) steps such as blank samples, replicates, and limit of detection (LOD) must be strictly implemented to ensure data representativeness [73]-[76]. For metal analysis, elemental determination is commonly performed using various modern analytical methods (Table 1), with spectroscopic techniques being the most widely applied because of their high sensitivity, accuracy, and multi-element capability:

- ICP-MS (Inductively Coupled Plasma - Mass Spectrometry): This is the most commonly used method due to its high sensitivity, good accuracy, and wide linear range, allowing simultaneous analysis of multiple trace metals in a single measurement [12], [60], [77]-[79].
- ICP-OES/ICP-AES (Inductively Coupled Plasma - Optical/Atomic Emission Spectrometry): Suitable for multi-metal analysis with high accuracy, especially in samples with medium to high concentrations [68], [80], [81].
- GF-AAS (Graphite Furnace Atomic Absorption Spectrometry): has high sensitivity, suitable for determining metals at very low concentrations [82].
- FAAS (Flame Atomic Absorption Spectrometry): is commonly used for metals at relatively high concentrations, with the advantages of low cost and simple operation [83].
- EDXRF (Energy Dispersive X-ray Fluorescence): allows for rapid, non-destructive analysis of samples, particularly useful in large-scale survey studies [84], [85].

On the other hand, determination of atmospheric Hg concentrations in both gaseous and particulate phases is commonly performed using cold vapor atomic fluorescence (CVAFS). Additionally, direct thermal analysis combined with adsorption on gold, using direct Hg analyzers (DMA), is also widely applied to determine the total amount of Hg accumulated on filter membranes (glass or quartz), representing PM samples. Compared to the traditional method based on acid digestion combined with CV-AFS, this technique has advantages in time consumption, simple procedure, and does not require the use of additional chemicals, thereby minimizing the risk of contamination during sample processing [30], [86].

4. Size-Resolved Characteristics And Governing Processes Of Metals In Atmospheric Aerosols.

Many studies have shown that metals in atmospheric PM exhibit distinct size-dependent distributions. Fine-mode dominated metals, especially Pb, Cd, and As, are commonly enriched in ≈ 0.1 - 1 µm and largely concentrated in $PM_{2.5}$ [12], [54], [60], [84], [87]. These elements are mainly associated with high-temperature sources such as coal combustion and metallurgical activities, where metals volatilize at high temperatures and subsequently condense onto fine particles during atmospheric cooling [9], [64], [66]. Consequently, their distributions are relatively stable, although small coarse contributions may arise from resuspension of contaminated dust. Pb is frequently concentrated in particles < 2.1 µm, while Cd and As strongly reflect condensation-driven formation [46], [87]. Studies in East Asia further showed that toxic metals such as Cd, Cr, Ni, and Pb were highly enriched in $PM_{2.5}$, often at levels indicating strong anthropogenic influence [9], [53], [68], [84], [88], [89]. However, these patterns are not fixed. Seasonal meteorology and pollution episodes can substantially modify particle-size distributions. In northern China, winter stagnation enhanced Cd, Cr, Ni, and Pb in the 0.847 - 2.14 µm fraction through intensified condensation and secondary aerosol formation [84]. In contrast, crustal metals including Al, Fe, Ba, Sr, and Ti were mainly found in coarse particles, confirming the consistent $PM_{2.5}$ enrichment of combustion-related metals [54], [68], [84], [88], [90]. Metals such as Zn, Cu, Ni, Cr, Mn, and V often show bimodal or multimodal patterns, reflecting multiple emission pathways [45], [46], [60], [91], [92]. These elements occupy an intermediate behavior between fine and coarse dominance because they originate from both thermal and mechanical sources. Zn and Cu are typical examples, arising from industrial activities as well as non-exhaust traffic emissions such as tire and brake wear, thus appearing in both $PM_{2.5}$ and coarse fractions [46]. Ni and V are linked to oil combustion, shipping, and marine aerosols, resulting in fine combustion particles together with coarse

sea-salt influenced fractions [60]. Coastal studies reported that V and Ni can be enriched in submicron PM while also showing coarse peaks due to sea-salt interaction and heterogeneous reactions [45], [60], [93]. European observations likewise found multimodal Ni and Zn distributions caused by overlapping industrial, traffic, and transported sources [12], [60]. These results suggest that bimodal distributions are characteristic of mixed-source environments rather than anomalies. Crustal metals such as Fe, Al, and Ca are generally associated with coarse particles because they mainly derive from soil resuspension, construction activities, and mechanical abrasion [54], [64]. Their distributions are usually dominated by particles > 2.5 µm, although partial shifts toward finer fractions may occur under polluted conditions or long-range transport [54], [91], [94], [95]. This pattern has been widely observed. For example, East Asian studies reported Al, Fe, Ca, Ba, and Ti mainly in coarse PM, clearly separated from anthropogenic metals enriched in $PM_{2.5}$ [54], [90]. In coastal Xiamen, Al, Ca, Fe, and Ti were concentrated in coarse particles, whereas anthropogenic metals were enriched in PM_1, highlighting the influence of mineral dust and marine sources on $PM_{2.5\text{-}10}$ composition [45]. In South Africa, Segakweng et al. [96] also identified Al, Fe, and Ca as dominant crustal metals, although 40 - 70 % of total metals were still detected in PM_1 during polluted periods, implying additional industrial and secondary contributions. Thus, coarse-mode dominance remains the main characteristic of crustal metals, but atmospheric processes may modify their distributions. Because coarse particles settle rapidly and often contain less soluble mineral phases, they are generally more important for local deposition than long-range transport [2], [45], [60]. Hg exhibits more dynamic size-resolved behavior than most particulate metals because PBM is strongly influenced by gas-particle partitioning and atmospheric chemical processes rather than direct emissions alone [97]-[99]. PBM is commonly enriched in ≈ 0.3 - 1.5 µm, similar to Pb, Cd, and As, with concentration maxima frequently observed within this size range, indicating important roles of condensation and heterogeneous reactions in its formation [49], [50], [51], [52]. However, Hg distributions are highly sensitive to environmental conditions. Variations in temperature, relative humidity, and oxidant levels can substantially modify PBM partitioning and particle-size patterns [98], [99]. In urban atmospheres, PBM is often concentrated in $PM_{2.5}$, whereas in coastal environments interactions with sea-salt aerosols may shift Hg toward coarse particles [93]. Seasonal changes may also transform unimodal distributions into bimodal or trimodal patterns [51], [52], [92], [93]. In addition, PBM is frequently associated with sulfate, nitrate, and organic matter, suggesting close coupling with secondary aerosol formation and aging processes [49], [50]. For example, Tang et al. [50] proposed that GOM generated during atmospheric transport can associate with gas-particle partitioning onto existing aerosols, thereby enhancing PBM formation, particularly during periods of elevated PM concentrations and active secondary aerosol formation.

Broadly, these patterns show that fine particles (< 2.5 µm), including PBM, are more favorable for long-range transport and inhalation exposure, whereas coarse particles are mainly linked to local sources and rapid deposition. Toxic metals enriched in submicron particles are of particular concern because of their high respiratory penetration. Nevertheless, actual size distributions are dynamic outcomes of source emissions interacting with atmospheric processes.

5. Human Respiratory Deposition Of Size-Resolved Metals: Current Knowledge And Health Implications

In recent years, respiratory deposition models such as the International Commission on Radiological Protection (ICRP) and Multiple-Path Particle Dosimetry (MPPD) models have been increasingly applied to studies of particle-bound metals for quantifying inhalation exposure and improving health risk assessment. Compared with approaches based only on ambient concentrations, these models estimate size-resolved deposition efficiencies in different regions of the respiratory tract, providing a more realistic representation of internal dose. Existing studies consistently show that particle size is the dominant factor controlling deposition: coarse particles are mainly removed in the head airway (HA) through inertial impaction, whereas fine and ultrafine particles can penetrate deeper into the tracheobronchial (TB) and alveolar (AR) regions, where residence times are longer and toxicological impacts may be greater [45], [46], [84]. A consistent finding is that accumulation-mode (≈ 0.1 - 1 µm) and ultrafine (< 0.1 µm) particles are particularly important for pulmonary delivery of toxic metals [12],

[46], [78]. Particles smaller than 0.1 µm are efficiently deposited in the alveolar region by diffusion, whereas minimum deposition often occurs near ~0.3 µm, representing the transition between diffusion- and inertia-dominated mechanisms [45], [84]. These patterns emphasize the importance of fine and ultrafine particles in transporting toxic metals to the deepest lung regions. Because fine and ultrafine particles can penetrate deeply into the alveolar region and potentially translocate into the bloodstream, inhalation of metal-rich particles may pose greater health risks than coarse particles. Previous studies have further suggested that ultrafine particles enriched with toxic metals can induce oxidative stress, inflammation, and neurological effects after reaching sensitive organs such as the brain [12], [46], [78]. Comparative studies also indicate systematic differences between deposition models. The ICRP model remains widely used because of its simplicity and empirical basis, but it applies a simplified single-path respiratory geometry and may underestimate lower-airway deposition, especially for ultrafine particles [9], [46], [78]. In contrast, the MPPD model incorporates realistic airway geometry and asymmetric branching, often producing higher and more physiologically representative deposition efficiencies in TB and AR regions for fine and ultrafine particles [45], [46]. For this reason, several recent studies have preferred the MPPD framework for size-resolved risk assessment. Field investigations under different pollution scenarios support these general patterns. In Zhuzhou, a non-ferrous smelting region, Lyu et al. [46] reported that the MPPD model estimated greater tracheobronchial and alveolar deposition than the ICRP model for $PM_{2.5}$-bound metals. Respiratory deposition fluxes ranged from 2.1×10^{-2} to 4.1×10^{3} ng h^{-1}, with the head airway receiving the highest share. Fine and ultrafine toxic-metal particles notably increased lung deposition during haze events. In Zhengzhou, Wang et al. found Cr, Cd, and Pb concentrated in ultrafine particles. Deposition-based exposure estimates were more realistic than ambient concentrations alone; Cd posed non-carcinogenic risk to children, while Cr exceeded carcinogenic limits. At an urban background site in Como, Northern Italy, Rovelli et al. [12] applied the MPPD model and found that Fe, Ba, and Cu, associated mainly with $PM_{1\text{-}2.5}$, deposited more efficiently in the HA region, whereas Pb, Ni, and Zn enriched in the accumulation mode showed relatively higher pulmonary deposition. Although hazard quotient values remained below unity, the study confirmed that size distribution strongly influences inhaled dose and risk. In Xiamen, Wu et al. [45] used the ICRP model and reported a bimodal total deposition pattern, with peaks in ultrafine and coarse fractions. Mean deposition followed HA (64 %) > AR (29 %) > TB (7 %). Importantly, risk estimates based on water-soluble metals were much lower than those using total concentrations, indicating that ignoring bioaccessibility may overestimate exposure. In general, available evidence shows that metals associated with fine and ultrafine particles have the greatest potential to penetrate into the alveolar region, whereas coarse-particle metals are deposited mainly in upper airways. Model choice can significantly affect estimated exposure, particularly for ultrafine particles and lower respiratory regions [9], [64], [78]. Despite growing research on metals such as Cr, Cd, Pb, Ni, V, Mn, Zn, and Cu, studies focusing on Hg remain scarce. This is an important gap because PBM is commonly enriched in fine and accumulation-mode particles that can efficiently reach the alveolar region. Integrating size-resolved deposition modeling with PBM observations is therefore essential for improving understanding of inhalation exposure and health risks of Hg, especially in urban and industrial environments dominated by $PM_{2.5}$ pollution.

6. Conclusion

Particle size is a key factor controlling the environmental behavior and health effects of atmospheric particulate matter. Total PM concentration alone cannot fully explain pollution impacts because particle size strongly affects atmospheric lifetime, long-range transport, deposition, chemical transformation, and human exposure. Over the past two decades, studies using cascade impactors, MOUDI systems, and modern analytical methods have substantially improved understanding of size-resolved metals and Hg. However, available studies remain unevenly distributed worldwide, with strong clustering in East Asia and Europe and relatively limited observations in tropical regions, particularly in Southeast Asia, Africa, and South America. Current evidence consistently shows that toxic metals such as Pb, Cd, and As are predominantly enriched in $PM_{2.5}$ and accumulation mode particles (≈ 0.1 - 1 µm), mainly due to combustion-related emissions and condensation processes following high-temperature release. In contrast, crustal metals such as Fe, Al, and Ca are generally associated with coarse particles derived

from soil dust and mechanical resuspension, whereas several metals, including Cu, Zn, Ni, Cr, and V, frequently exhibit bimodal distributions reflecting mixed anthropogenic and natural sources. Hg exhibits more complex atmospheric behavior because it is primarily emitted in gaseous form and subsequently transformed into PBM, which is commonly enriched in accumulation mode particles. These size-dependent distributions can be significantly influenced by atmospheric aging, secondary aerosol formation, and meteorological conditions. From a health perspective, fine and ultrafine particles are of greatest concern because they can penetrate deeply into the respiratory tract and enhance inhalation exposure to toxic metals and PBM. Existing respiratory deposition studies indicate that accumulation mode and ultrafine (< 0.1 μm) particles contribute substantially to pulmonary and alveolar deposition, highlighting the importance of particle size in determining internal dose and health risk. Despite substantial progress, important knowledge gaps remain regarding Hg behavior, metal bioavailability, and long-term observations in tropical, coastal, industrial, and biomass-burning regions. Future studies should integrate field measurements, atmospheric modeling, respiratory deposition assessment, and health-risk evaluation to better understand the environmental fate and health implications of size-resolved atmospheric metals and Hg.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Table 1. *Summary of previous studies on size-resolved atmospheric metals, including study sites, target metals, particle-size fractions, and instruments.*

Reference	Sites	Metals	Size-segregated	Analyzed instrument	Sampling instrument
[99]	Southern Spain	Cr, Co, Ni, Zn	<0.33 - 17 μm	ICP-MS	Mark III cascade impactor
[53]	Beijing, China	V, Cr, Mn, Fe, Cu, Zn, As, Cd, Sb, Ba, Pb	<0.26 - 10 μm	ICP-MS/ICP-AES	7-stage cascade impactor sampler
[64]	Shanghai, China	Mn, Co, Cu, As, Ba, Pb, Cr, Fe, Ni, Zn, Se, Cd,	0.028 - 9.92 μm	ICP-MS	Low pressure cascade impactor
[68]	Nanjing, China	Fe, As, Cd, Cr, Cu, Mn, Ni, Pb, Zn	0.4 - 9.0 μm	ICP-OES	High volume air sampler
[100]	Delhi, India	Mn, Fe, Pb, Cr, Cd, Cu, Ni	<0.7 - >10.9 μm	AAS	Five-stage cascade particulate separator
[12]	Como, Italy	Cr, Mn, Fe, Ni, Cu, Zn, Ba, Pb	0.028 - 2.4 μm	LA-ICP-MS	13-stage low pressure impactor
[60]	Turin, Italy	As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, V, Zn	0.54 - 11.0 μm	SF-ICP-MS	8-stages Andersen MkII nonviable cascade impactor
[91]	Sarajevo, Bosnia	Co, Cu, Mn, Fe	<0.49 - >7.2 μm	AAS-GF	Six-stage cascade impactor
[65]	Antarctica	V, Mn, Ni, Cu, Zn, Pb	0.056 - 18 μm	SF-ICP-MS	10-stage Micro-Orifice Uniform Deposit Impactor™

[59]	London, UK	V, Cr, Mn, Fe, Ni, Cu, Zn, Sb, Ba, Pb	0.3 - 10 µm	SR-XRF	Rotating drum impactors
[77]	Beijing, China	Mn, Fe, Co, Ni, Cu, Zn, Cd, Ba,Pb	0.43 - 9.0 µm	ICP-MS	Two nine-stage samplers
[9]	Dunkirk, France	As, Ba, Cd, Co, Cr, Cu, Mn, Mo, Ni, Pb, Sb, V, Zn	0.056 - 18 µm	ICP-AES/MS	13-stages of cascade impactors
[46]	Zhuzhou, China	V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Cd, Sb, Ba, Pb	0.43 - 9.0 µm	ICP-MS	Anderson eight-stage cascade impactor
[45]	Xiamen, China	Fe, V, Cr, Mn, Ni, Cu, Zn, As, Se, Cd, Ba, Pb	<0.25 - 1.4; 1.4 - >16 µm	ICP-MS	Micro-Orifice Uniform Deposition Impactor sampler
[94]	Linfen, China	Ba, Mn, Co, Ni, Cu, Zn, Cd, Pb, V, Cr, As, Se	0.43 - 10 µm	ICP-MS	Anderson eightstage cascade impactor
[66]	Tianjin, China	V, Cr, Mn, Fe, Ni, Cu, Zn, Pb, As, Cd	0.006 - 9.8 µm	ICP-AES	Electrical Low Pressure Impactor (ELPI+)
[95]	Beijing, China	V, Cr, Mn, Fe, Cu, Zn, As, Cd, Pb	0.43 - 9.0 µm	ICP-MS	Nine-stage samplers
[92]	New Jersey, USA	Al, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Sb, V and Zn	0.18 - 18 µm	ICP-MS	Eight-stage MOUDI
[67]	Houston, USA	Fe, V, Cr, Mn, Ni, Cu, Zn, As, Cd, Pb, Se, Sb, Ba	<0.25 - >2.5 µm	ICP-MS	Personal Cascade Impactor Samplers (PCISs)
[84]	Zhengzhou, China	V, Cr, Mn, Fe, Ni, Cu, Zn, As, Se, Cd, Sn, Sb, Ba, Pb	0.006 - 8.86 µm	XRF	Fourteen-stage electrical low pressure impactor
[61]	Bangkok, Thailand	V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Mo, Cd, Sb, Ba, Pb	0.028 - 9.9 µm	ICP-MS	Electrical Low Pressure Impactor (ELPI)
[61]	Chiang Mai, Thailand	Zn, Pb, Ni, Cd	<0.49 - 10 µm,	ICP-MS/OES	High-volume air sampler
[54]	Beijing, China	V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Cd, Sn, Sb, Ba, Hg, Pb	0.028 - 9.92 µm	ICP-MS/AES	Thirteen-stage low pressure cascade impactor
[79]	Dalian, China	Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Cd, Ba, Hg, Pb	<0.49 - 7.2 µm	ICP-MS	Six-stage High Volume Air Flow HVS sampler
[78]	Porto, Portugal	Cr, Co, Ni, Cu, Zn, As, Se, Cd, Sb, Ba, Hg, Pb	0.0308 - 2.5 µm	ICP-MS	Low-pressure impactor
[93]	USA	Hg	<0.4 - >10 µm	Tekran 1135.	Andersen Mark II Cascade Impactors with 10 filters

[71]	Seoul & Chuncheon, Korea	Hg	<0.4 - 10 µm	a Tekran 2537B	MOUDI
[51]	USA	Hg	0.01 - 18 µm	CVAAS	MOUDI and Nano-MOUDI samplers
[69]	Guizhou, China	Hg	TSP; PM_{10}; $PM_{2.5}$	CVAFS	Intelligent medium-volume sampler
[52]	Zabrze, Poland	Hg	0.03 - 40 µm	CVAAS	13-stage Dekati low pressure impactor
[49]	Shanghai, China	Hg	<1.1 - >7.0 µm	CVAAS	Kimoto-200F high-volume airborne particle sampler
[55]	Nanjing, China	Hg	<1.6 - >18 µm	CVAFS	Andersen eight-stage cascade impactor
[56]	Multi sites, China	Hg	0.01 - 18 µm	DMA-80	13-staged size-specific particle samplers, MOUDI sampler
[57]	Multi sites, Taiwan	Hg	1.0 - 18 µm	CVAFS	MOUDI
[50]	Beijing, China	Hg	0.056 - 10 µm	LUMEX 915 M + pyro attachment	NCTU Micro-orifice Cascade Impactor
[101]	Multi sites, China	Hg	<2.5; 2.5-10; 10-100 µm	PYRO-915+ / RA-915+	Medium-volume sampler
[86]	Multi sites, Türkiye	Hg	<0.43 - >8 µm	FIA-AS + GF-AAS	Andersen 8-stage cascade impactor

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